

Beyond Collinearity in the N(e,e'q) Process

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Abstract

We discuss a few examples of structure functions for polarized, semi-inclusive scattering processes to show the richness of structure. Then we indicate how polarization and particle production can be used to study the quark and gluon structure of hadrons going further than the well-known parton densities and fragmentation functions. We also emphasize how single spin asymmetries in leptonproduction may shed light on explanations for single spin asymmetries in pion production in pp collisions.

1 Structure functions

The object of interest for 1-particle inclusive leptonproduction, the hadronic tensor, is given by

$$2M\mathcal{W}_{\mu\nu}^{(\ell H)}(q; PS; P_h S_h) = \frac{1}{(2\pi)^4} \int \frac{d^3 P_X}{(2\pi)^3 2P_X^0} (2\pi)^4 \delta^4(q + P - P_X - P_h) \times \langle PS | J_\mu(0) | P_X; P_h S_h \rangle \langle P_X; P_h S_h | J_\nu(0) | PS \rangle, \quad (1)$$

where P , S and P_h , S_h are the momenta and spin vectors of target hadron and produced hadron, q is the (spacelike) momentum transfer with $-q^2 = Q^2$ sufficiently large. The kinematics is illustrated in Fig. 1, where also the scaling variables are introduced. For inclusive

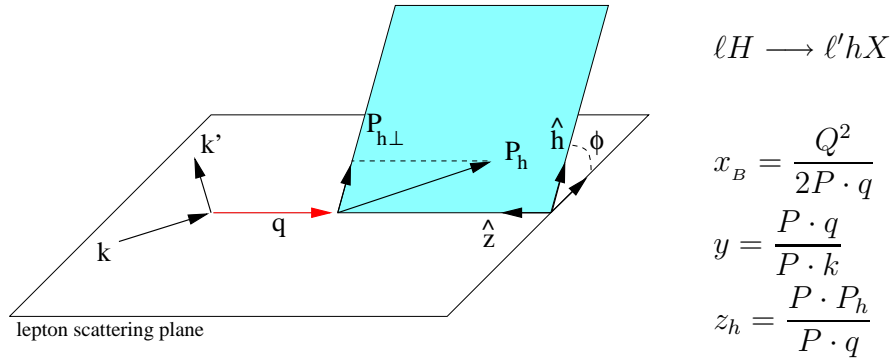


Figure 1: *Kinematics for 1-particle inclusive leptonproduction.*

scattering (unpolarized lepton and hadron, γ -exchange) the most general symmetric part of

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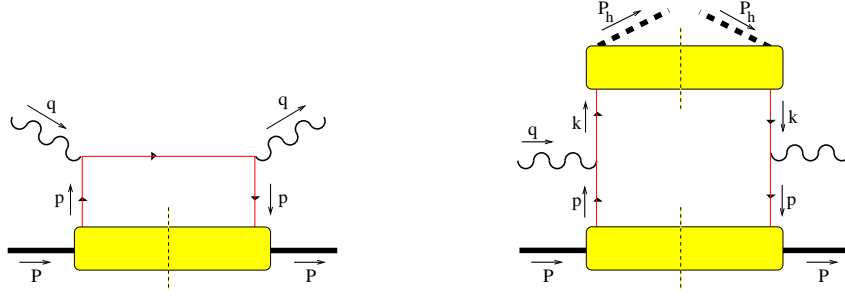


Figure 2: *The simplest (parton-level) diagrams representing the squared amplitude in lepton hadron inclusive scattering (left) en semi-inclusive scattering (right).*

the hadronic tensor is²

$$2MW_S^{\mu\nu}(q, P) = \underbrace{\left(-g^{\mu\nu} + \hat{q}^\mu \hat{q}^\nu - \hat{t}^\mu \hat{t}^\nu\right)}_{-g_\perp^{\mu\nu}} F_1 + \underbrace{\hat{t}^\mu \hat{t}^\nu \left(\frac{F_2}{2x_B} - F_1\right)}_{F_L} \quad (2)$$

Combined with the leptonic part, one obtains the cross section for unpolarized leptons off an unpolarized target

$$\frac{d\sigma_{OO}}{dx_B dy} = \frac{4\pi \alpha^2 x_B s}{Q^4} \left\{ \left(1 - y + \frac{1}{2} y^2\right) F_T + (1 - y) F_L \right\}. \quad (3)$$

In order to calculate the hadronic tensor, a diagrammatic expansion is written down starting with the well-known handbag diagram (see Fig. 2, left), yielding the parton model results for the structure functions,

$$F_T(x_B, Q) = F_1(x_B, Q) = \frac{1}{2} \sum_{a, \bar{a}} e_a^2 f_1^a(x_B), \quad (4)$$

$$F_L(x_B, Q) = 0, \quad (5)$$

expressed in terms of the quark distribution f_1^a (a is the flavor index). The summation runs over quarks and antiquarks. The most general antisymmetric part of the hadronic tensor involves polarized leptons and hadrons and is for γ -exchange given by

$$2MW_A^{\mu\nu}(q, P, S) = \underbrace{-i \lambda \frac{\epsilon^{\mu\nu\rho\sigma} P_\rho q_\sigma}{P \cdot q}}_{-i \lambda \epsilon_\perp^{\mu\nu}} g_1 + i \frac{2Mx_B}{Q} \hat{t}^{[\mu} \epsilon_\perp^{\nu]\rho} S_{\perp\rho} g_T \quad (6)$$

with the longitudinal polarization $\lambda \equiv q \cdot S / q \cdot P$ and S_\perp the transverse spin vector obtained with the help of $g_\perp^{\mu\nu}$. The cross section for polarized leptons of a longitudinally polarized target becomes

$$\frac{d\sigma_{LL}}{dx_B dy} = \lambda_e \frac{4\pi \alpha^2}{Q^2} \left\{ \lambda \left(1 - \frac{y}{2}\right) g_1 - |S_\perp| \cos \phi_S^\ell \frac{2Mx_B}{Q} \sqrt{1 - y} g_T \right\}, \quad (7)$$

$$\hat{q}^\mu = q^\mu / Q, \quad \hat{t}^\mu = \tilde{P}^\mu / \sqrt{\tilde{P}^2} = \left(P^\mu - \frac{P \cdot q}{q^2} q^\mu\right) / \sqrt{\tilde{P}^2}.$$

with the parton model results

$$g_1(x_B, Q) = \frac{1}{2} \sum_{a, \bar{a}} e_a^2 g_1^a(x_B), \quad (8)$$

$$g_T(x_B, Q) = (g_1 + g_2)(x_B, Q) = \frac{1}{2} \sum_{a, \bar{a}} e_a^2 g_T^a(x_B). \quad (9)$$

The function g_1^a is the quark helicity distribution. The function g_T^a is a higher twist distribution.

Proceeding to the 1-particle inclusive case for unpolarized lepton and hadron³ we obtain generally for the symmetric part of the hadronic tensor

$$\begin{aligned} 2M\mathcal{W}_S^{\mu\nu}(q, P, P_h) = & -g_\perp^{\mu\nu} \mathcal{H}_T + \hat{t}^\mu \hat{t}^\nu \mathcal{H}_L \\ & + \hat{t}^{\{\mu} \hat{h}^{\nu\}} \mathcal{H}_{LT} + \left(2 \hat{h}^\mu \hat{h}^\nu + g_\perp^{\mu\nu} \right) \mathcal{H}_{TT}, \end{aligned} \quad (10)$$

leading to the unpolarized cross section

$$\begin{aligned} \frac{d\sigma_{OO}}{dx_B dy dz_h d^2q_T} = & \frac{4\pi \alpha^2 s}{Q^4} x_B z_h \left\{ \left(1 - y + \frac{1}{2} y^2 \right) \mathcal{H}_T + (1 - y) \mathcal{H}_L \right. \\ & \left. - (2 - y) \sqrt{1 - y} \cos \phi_h^\ell \mathcal{H}_{LT} + (1 - y) \cos 2\phi_h^\ell \mathcal{H}_{TT} \right\}. \end{aligned} \quad (11)$$

We will come back to parton expressions for semi-inclusive structure functions later with emphasis on the azimuthal dependence, such as the $\cos \phi_h^\ell$ and $\cos 2\phi_h^\ell$ parts depending on the azimuthal angle between the lepton scattering plane and the production plane (see Fig. 1). Limiting ourselves to unpolarized hadrons, the antisymmetric part of the hadronic tensor is

$$2M\mathcal{W}_A^{\mu\nu}(q, P, P_h) = -i \hat{t}^{[\mu} \hat{h}^{\nu]} \mathcal{H}'_{LT}, \quad (12)$$

leading to the cross section for polarized leptons from an unpolarized target (single spin asymmetry)

$$\frac{d\sigma_{LO}}{dx_B dy dz_h d^2q_T} = \lambda_e \frac{4\pi \alpha^2}{Q^2} z_h \sqrt{1 - y} \sin \phi_h^\ell \mathcal{H}'_{LT}. \quad (13)$$

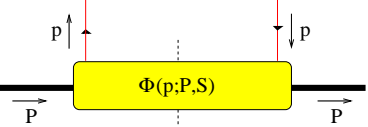
Our aim in studying leptonproduction is the study of the quark and gluon structure of the hadronic target using the known framework of Quantum Chromodynamics (QCD). Thus, as a theorist the aim is to calculate the hadronic tensor $W_{\mu\nu}$ by making a diagrammatic expansion. Already at the simplest level (Fig. 2) a problem is encountered, namely there are hadrons involved for which QCD does not provide rules. Thus, *soft parts* are identified that allow inclusion of hadrons in the field theoretical framework. Luckily it turns out that for $Q^2 \rightarrow \infty$ only a limited number of diagrams is needed.

2 Soft parts

$$\begin{aligned} \hat{q}^\mu &= q^\mu / Q, \quad \hat{t}^\mu = (q^\mu + 2x_B P^\mu) / Q, \\ q_T^\mu &= q^\mu + x_B P^\mu - P_h^\mu / z_h = -P_{h\perp}^\mu / z_h \equiv -Q_T \hat{h}^\mu. \end{aligned}$$

2.1 Definition as quark operators

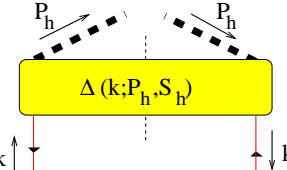
Next, we look in more detail to the soft parts, such as appear for instance in the parton diagram. They can be written down in terms of quark and gluon fields as illustrated below. They are characterized by the fact that the momenta are *soft* with respect to each other. We have for the distribution part [1, 2]



represented by

$$\Phi_{ij}(p, P, S) = \frac{1}{(2\pi)^4} \int d^4x e^{ip \cdot x} \langle P, S | \bar{\psi}_j(0) \psi_i(x) | P, S \rangle, \quad (14)$$

and the fragmentation part [3]



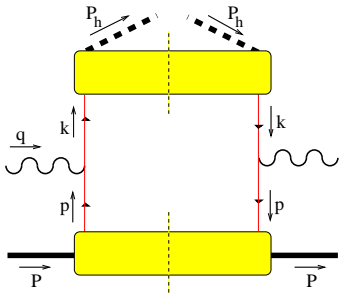
represented by

$$\Delta_{ij}(k, P_h, S_h) = \sum_X \frac{1}{(2\pi)^4} \int d^4x e^{ik \cdot x} \langle 0 | \psi_i(x) | P_h, S_h; X \rangle \langle P_h, S_h; X | \bar{\psi}_j(0) | 0 \rangle. \quad (15)$$

In order to find out which information in the soft parts Φ and Δ is important in a hard process one needs to realize that the hard scale Q leads in a natural way to the use of lightlike vectors n_+ and n_- satisfying $n_+^2 = n_-^2 = 0$ and $n_+ \cdot n_- = 1$. For 1-particle inclusive scattering one parametrizes the momenta

$$\left. \begin{aligned} q^2 &= -Q^2 \\ P^2 &= M^2 \\ P_h^2 &= M_h^2 \\ 2P \cdot q &= \frac{Q^2}{x_B} \\ 2P_h \cdot q &= -z_h Q^2 \end{aligned} \right\} \longleftrightarrow \left\{ \begin{aligned} P_h &= \frac{z_h Q}{\sqrt{2}} n_- + \frac{M_h^2}{z_h Q \sqrt{2}} n_+ \\ q &= \frac{Q}{\sqrt{2}} n_- - \frac{Q}{\sqrt{2}} n_+ + q_T \\ P &= \frac{x_B M^2}{Q \sqrt{2}} n_- + \frac{Q}{x_B \sqrt{2}} n_+ \end{aligned} \right.$$

Comparing the power of Q with which the momenta in the soft and hard part appear one immediately is led to $\int dp^- \Phi(p, P, S)$ and $\int dk^+ \Delta(k, P_h, S_h)$ as the relevant quantities to investigate.



part	'components'		
	-	+	
$q \rightarrow h$	$\sim Q$	$\sim 1/Q$	$\rightarrow \int dk^+ \dots$
HARD	$\sim Q$	$\sim Q$	
$H \rightarrow q$	$\sim 1/Q$	$\sim Q$	$\rightarrow \int dp^- \dots$

2.2 Analysis of soft parts: distribution and fragmentation functions

Hermiticity, parity and time reversal invariance (T) constrain the quantity $\Phi(p, P, S)$ and therefore also the Dirac projections $\Phi^{[\Gamma]}$ defined as

$$\begin{aligned}\Phi^{[\Gamma]}(x, \mathbf{p}_T) &= \int dp^- \frac{\text{Tr}[\Phi\Gamma]}{2} \\ &= \int \frac{d\xi^- d^2\xi_T}{2(2\pi)^3} e^{ip\cdot\xi} \langle P, S | \bar{\psi}(0) \Gamma \psi(\xi) | P, S \rangle \Big|_{\xi^+=0},\end{aligned}\quad (16)$$

which is a lightfront ($\xi^+ = 0$) correlation function. The relevant projections in Φ that are important in leading order in $1/Q$ in hard processes are

$$\Phi^{[\gamma^+]}(x, \mathbf{p}_T) = f_1(x, \mathbf{p}_T^2) - \frac{\epsilon_T^{ij} k_{Ti} S_{Tj}}{M} f_{1T}^\perp(x, \mathbf{k}_T), \quad (17)$$

$$\Phi^{[\gamma^+\gamma_5]}(x, \mathbf{p}_T) = \lambda g_{1L}(x, \mathbf{p}_T^2) + \frac{(\mathbf{p}_T \cdot \mathbf{S}_T)}{M} g_{1T}(x, \mathbf{p}_T^2) \quad (18)$$

$$\begin{aligned}\Phi^{[i\sigma^{i+}\gamma_5]}(x, \mathbf{p}_T) &= S_T^i h_1(x, \mathbf{p}_T^2) + \frac{\lambda p_T^i}{M} h_{1L}^\perp(x, \mathbf{p}_T^2) \\ &\quad - \frac{(p_T^i p_T^j + \frac{1}{2} \mathbf{p}_T^2 g_T^{ij}) S_{Tj}}{M^2} h_{1T}^\perp(x, \mathbf{p}_T^2) \\ &\quad - \frac{\epsilon_T^{ij} k_{Tj}}{M} h_1^\perp(x, \mathbf{k}_T),\end{aligned}\quad (19)$$

Here $x = p^+/P^+$, $\lambda = MS^+/P^+$ and S_T is the spin-component projected out by $g_T^{\mu\nu} = g^{\mu\nu} - n_+^\mu n_-^\nu$, They satisfy $\lambda^2 + \mathbf{S}_T^2 = 0$. The tensor $\epsilon_T^{\mu\nu} = \epsilon^{\rho\sigma\mu\nu} n_{+\rho} n_{-\sigma}$.

All functions appearing above can be interpreted as momentum space densities, as illustrated in Fig. 3. The ones denoted [4] f_{\dots} involve the operator structure $\bar{\psi}\gamma^+\psi = \psi_+^\dagger\psi_+$, where $\psi_+ = P_+\psi$ with $P_+ = \gamma^-\gamma^+/2$. This operator projects on the so-called good component of the Dirac field, which can be considered as a *free* dynamical degree of freedom in front form quantization. It is precisely in this sense that partons measured in hard processes are free. The functions g_{\dots} and h_{\dots} appearing above are differences of densities involving good fields, but in addition projection operators $P_{R/L} = (1 \pm \gamma_5)/2$ and $P_{\uparrow/\downarrow} = (1 \pm \gamma^1\gamma_5)/2$, all of which commute with P_+ . To be precise for the functions g_{\dots} one has $\bar{\psi}\gamma^+\gamma_5\psi = \psi_{+R}^\dagger\psi_{+R} - \psi_{+L}^\dagger\psi_{+L}$ while in the case of h_{\dots} one has $\bar{\psi}\sigma^{1+}\gamma_5\psi = \psi_{+\uparrow}^\dagger\psi_{+\uparrow} - \psi_{+\downarrow}^\dagger\psi_{+\downarrow}$.

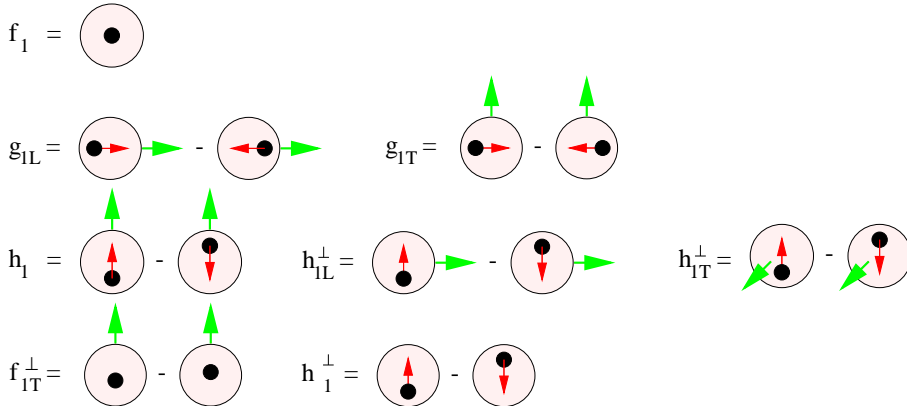


Figure 3: Interpretation of the functions in the leading Dirac projections of Φ .

The functions f_{1T}^\perp and h_1^\perp are special. Applying time-reversal shows that these functions should disappear from the parametrization of the matrix element Φ . However, application of time-reversal invariance for k_T -dependent functions involves a few tricky points related to poles in gluonic matrix elements [5] and we decided here to take the purely phenomenological approach and keep these so-called T-odd functions. The functions describe the possible appearance of unpolarized quarks in a transversely polarized nucleon (f_{1T}^\perp) or transversely polarized quarks in an unpolarized hadron (h_1^\perp) and lead to single-spin asymmetries in various processes [6, 7].

It is useful to remark here that flavor indices have been omitted, i.e. one has f_1^u , f_1^d , etc. At this point it may also be good to mention other notations used frequently such as $f_1^u(x) = u(x)$, $g_1^u(x) = \Delta u(x)$, $h_1^u(x) = \Delta_T u(x)$, etc. These x -dependent functions are the ones obtained after integration over \mathbf{p}_T .

The analysis of the soft part Φ can be extended to other Dirac projections. Limiting ourselves to \mathbf{p}_T -averaged functions one finds

$$\Phi^{[1]}(x) = \frac{M}{P^+} e(x), \quad (20)$$

$$\Phi^{[\gamma^i \gamma_5]}(x) = \frac{M S_T^i}{P^+} g_T(x), \quad (21)$$

$$\Phi^{[i\sigma^{+-} \gamma_5]}(x) = \frac{M}{P^+} \lambda h_L(x). \quad (22)$$

Lorentz covariance requires for these projections on the right hand side a factor M/P^+ , which as can be seen from the parametrization of momenta produces a suppression factor M/Q and thus these functions appear at subleading order in cross sections. The constraints on Φ lead to relations between the above higher twist functions and \mathbf{p}_T/M -weighted functions [8, 9], e.g.

$$g_2 = g_T - g_1 = \frac{d}{dx} g_{1T}^{(1)}, \quad (23)$$

where

$$g_{1T}^{(1)}(x) = \int d^2 \mathbf{p}_T \frac{\mathbf{p}_T^2}{2M^2} g_{1T}(x, \mathbf{p}_T). \quad (24)$$

We will use the index (1) to indicate a \mathbf{p}_T^2 -moment of the above type.

Just as for the distribution functions one can perform an analysis of the soft part describing the quark fragmentation [9]. The Dirac projections are

$$\begin{aligned} \Delta^{[\Gamma]}(z, \mathbf{k}_T) &= \int dk^+ \frac{\text{Tr}[\Delta \Gamma]}{4z} \\ &= \sum_X \int \frac{d\xi^+ d^2 \xi_T}{4z (2\pi)^3} e^{ik \cdot \xi} \text{Tr} \langle 0 | \psi(x) | P_h, X \rangle \langle P_h, X | \bar{\psi}(0) \Gamma | 0 \rangle \Big|_{\xi^- = 0}. \end{aligned} \quad (25)$$

The relevant projections in Δ that appear in leading order in $1/Q$ in hard processes are for the case of no final state polarization,

$$\Delta^{[\gamma^-]}(z, \mathbf{k}_T) = D_1(z, -z\mathbf{k}_T), \quad (26)$$

$$\Delta^{[i\sigma^{i-} \gamma_5]}(z, \mathbf{k}_T) = \frac{\epsilon_T^{ij} k_T^j}{M_h} H_1^\perp(z, -z\mathbf{k}_T). \quad (27)$$

The arguments of the fragmentation functions D_1 and H_1^\perp are chosen to be $z = P_h^-/k^-$ and $\mathbf{P}_{h\perp} = -z\mathbf{k}_T$. The first is the (lightcone) momentum fraction of the produced hadron, the

$$D_1 = \text{circle with a black dot} \quad H_1^\perp = \text{circle with a black dot and a red arrow pointing up} - \text{circle with a black dot and a red arrow pointing down}$$

Figure 4: *Interpreting the leading Dirac projections of Δ for unpolarized hadrons.*

second is the transverse momentum of the produced hadron with respect to the quark. The fragmentation function D_1 is the equivalent of the distribution function f_1 . It can be interpreted as the probability of finding a hadron h in a quark. Noteworthy is here the appearance of the function H_1^\perp , interpretable as the different production probability of unpolarized hadrons from a transversely polarized quark (see Fig. 4). It is the equivalent of the distribution function h_1^\perp . For the matrix element Δ involving out-states $|P_h, X\rangle$ (in contrast to the plane waves in Φ), the appearance of these functions is completely natural, since final state interactions prohibit constraints from time-reversal invariance. Also this function leads to single-spin asymmetries [10, 11]

After \mathbf{k}_T -averaging one is left with the functions $D_1(z)$ and the \mathbf{k}_T/M -weighted result $H_1^{\perp(1)}(z)$. We summarize the full analysis of the soft part with a table of distribution and fragmentation functions for unpolarized (U), longitudinally polarized (L) and transversely polarized (T) targets, distinguishing leading (twist two) and subleading (twist three, appearing at order $1/Q$) functions and furthermore distinguishing the chirality [4]. The functions printed in boldface survive after integration over transverse momenta. We have for the distributions included a separate table with distribution functions that can exist without the T constraint.

Classification of distribution and fragmentation functions:

DISTRIBUTIONS (T-even)				DISTRIBUTIONS (T-odd)			
$\Phi^{[\Gamma]}$		chirality		$\Phi^{[\Gamma]}(x, \mathbf{k}_T)$		chirality	
		even	odd			even	odd
twist 2	U	f_1		twist 2	U	—	h_1^\perp
	L	g_{1L}	h_{1L}^\perp	twist 2	L	—	—
	T	g_{1T}	h_1 h_{1T}^\perp	twist 2	T	f_{1T}^\perp	—
twist 3	U	f^\perp	e	twist 3	U	—	h
	L	g_L^\perp	h_L	twist 3	L	f_L^\perp	e_L
	T	g_T g_T^\perp	h_T h_T^\perp	twist 3	T	f_T	e_T

FRAGMENTATION			
$\Delta^{[\Gamma]}$		chirality	
		even	odd
twist 2	U	D_1	H_1^\perp
	L	G_{1L}	H_{1L}^\perp
	T	G_{1T} D_{1T}^\perp	H_1 H_{1T}^\perp
twist 3	U	D^\perp	E H
	L	G_L^\perp D_L^\perp	E_L H_L
	T	G_T G_T^\perp D_T	E_T H_T H_T^\perp

3 Cross sections for lepton-hadron scattering

After the analysis of the soft parts, the next step is to find out how one obtains the information on the various correlation functions from experiments, in this paper in particular lepton-hadron

scattering via one-photon exchange as discussed in section 1. To get the leading order result for semi-inclusive scattering it is sufficient to compute the diagram in Fig. 2 (right) by using QCD and QED Feynman rules in the hard part and the matrix elements Φ and Δ for the soft parts, parametrized in terms of distribution and fragmentation functions. The results are:

Cross sections (leading in $1/Q$)

$$\frac{d\sigma_{OO}}{dx_B dy dz_h} = \frac{2\pi\alpha^2 s}{Q^4} \sum_{a,\bar{a}} e_a^2 \left(1 + (1-y)^2\right) x_B f_1^a(x_B) D_1^a(z_h) \quad (28)$$

$$\frac{d\sigma_{LL}}{dx_B dy dz_h} = \frac{2\pi\alpha^2 s}{Q^4} \lambda_e \lambda \sum_{a,\bar{a}} e_a^2 y(2-y) x_B g_1^a(x_B) D_1^a(z_h) \quad (29)$$

Comparing with the expressions in section 1, one can identify the structure function \mathcal{H}_T and deduce that in leading order α_s^0 the function $\mathcal{H}_L = 0$.

It is not difficult to give some general rules on how the distribution and fragmentation functions are encountered in experiments. I will just give a few examples.

In 1-particle inclusive processes, one actually becomes sensitive to quark transverse momentum dependent distribution functions. One finds at order $1/Q$ the following nonvanishing azimuthal asymmetries [12]:

Azimuthal asymmetries for unpolarized targets (higher twist)

$$\begin{aligned} \int d^2\mathbf{q}_T \frac{Q_T}{M} \cos(\phi_h^\ell) \frac{d\sigma_{OO}}{dx_B dy dz_h d^2\mathbf{q}_T} &\equiv \left\langle \frac{Q_T}{M} \cos(\phi_h^\ell) \right\rangle_{OO} \\ &= -\frac{2\pi\alpha^2 s}{Q^4} 2(2-y)\sqrt{1-y} \sum_{a,\bar{a}} e_a^2 \left\{ \frac{2M}{Q} x_B^2 f^{\perp(1)a}(x_B) D_1^a(z_h) \right. \\ &\quad \left. + \frac{2M_h}{Q} x_B f_1^a(x_B) \frac{\tilde{D}^{\perp(1)a}(z_h)}{z_h} \right\} \quad (30) \end{aligned}$$

$$\text{note: } \tilde{D}^{\perp a}(z) = D^{\perp a}(z) - z D_1^a(z),$$

$$\left\langle \frac{Q_T}{M} \sin(\phi_h^\ell) \right\rangle_{OO} = \frac{2\pi\alpha^2 s}{Q^4} \lambda_e 2y\sqrt{1-y} \sum_{a,\bar{a}} e_a^2 \frac{2M}{Q} x_B^2 \tilde{e}^a(x_B) H_1^{\perp(1)a}(z_h) \quad (31)$$

$$\text{note: } \tilde{e}^a(x) = e^a(x) - \frac{m_a}{M} \frac{f_1^a(x)}{x}.$$

The first weighted cross section given here involves the structure function \mathcal{H}_{LT} and contains the twist three distribution function f^\perp and the fragmentation function D^\perp . The second cross section involves the structure function containing the distribution function e and the time-reversal odd fragmentation function H_1^\perp . The tilde functions that appear in the cross sections are in fact precisely the so-called interaction dependent parts of the twist three functions. They would vanish in any naive parton model calculation in which cross sections are obtained by folding electron-parton cross sections with parton densities. Considering the relation for \tilde{e} one can state it as $x e(x) = (m/M) f_1(x)$ in the absence of quark-quark-gluon correlations. The inclusion of the latter also requires diagrams dressed with gluons.

In the introduction we already mentioned the $\cos 2\phi$ asymmetry in unpolarized lepton production. This asymmetry requires the presence of a T-odd distribution function. But note that the effect is leading order in $1/Q$, i.e. nonvanishing at large Q .

Azimuthal asymmetries for unpolarized targets (leading twist)

$$\left\langle \frac{Q_T^2}{MM_h} \cos(2\phi_h^\ell) \right\rangle_{OO} = \frac{4\pi\alpha^2 s}{Q^4} 4(1-y) \sum_{a,\bar{a}} e_a^2 x_B h_1^{\perp(1)a}(x_B) H_1^{\perp(1)a}. \quad (32)$$

As a final example we mention the possibility to use leptonproduction to resolve issues in other processes. For example, the single spin (left-right) asymmetry observed in $p^\uparrow p \rightarrow \pi X$ could be attributed to a T-odd effect in the initial state (Sivers effect) or a similar effect in the final state (Collins effect). These two effects or the relative importance of them could be decided by considering two different asymmetries in leptonproduction. Let's consider for simplicity the two effects separately. In case one blames the single spin asymmetry fully on the initial state [6, 7] it only involves the distribution function f_{1T}^\perp , while if it is blamed on the final state [10, 11] it only involves the fragmentation function H_1^\perp . By considering the asymmetries in leptonproduction, mentioned below one could decide which effect is actually responsible [13].

Single spin azimuthal asymmetries for transversely polarized targets

$$\left\langle \frac{Q_T}{M_h} \sin(\phi_h^\ell - \phi_S^\ell) \right\rangle_{OTO} = \frac{2\pi\alpha^2 s}{Q^4} |\mathbf{S}_T| \left(1 - y - \frac{1}{2}y^2\right) \sum_{a,\bar{a}} e_a^2 x_B f_{1T}^{\perp(1)a}(x_B) D_1^a(z_h) \quad (33)$$

$$\left\langle \frac{Q_T}{M_h} \sin(\phi_h^\ell + \phi_S^\ell) \right\rangle_{OTO} = \frac{4\pi\alpha^2 s}{Q^4} |\mathbf{S}_T| (1-y) \sum_{a,\bar{a}} e_a^2 x_B h_1^a(x_B) H_1^{\perp(1)a}(z_h), \quad (34)$$

4 Concluding remarks

In the previous section some results for 1-particle inclusive lepton-hadron scattering have been presented. Several other effects are important in these cross sections, such as target fragmentation, the inclusion of gluons in the calculation to obtain color-gauge invariant definitions of the correlation functions and an electromagnetically gauge invariant result at order $1/Q$ and finally QCD corrections which can be moved back and forth between hard and soft parts, leading to the scale dependence of the soft parts and the DGLAP equations.

In my talk I have tried to indicate why semi-inclusive, in particular 1-particle inclusive lepton-hadron scattering, can be important. The goal is the study of the quark and gluon structure of hadrons, emphasizing the dependence on transverse momenta of quarks. The reason why this prospect is promising is the existence of a field theoretical framework that allows a clean study involving well-defined hadronic matrix elements.

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